Expected end-to-end latency of cause-effect chains

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End-to-end latency research focuses on the **worst case**

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Controllers designed for the **average case***
perform better

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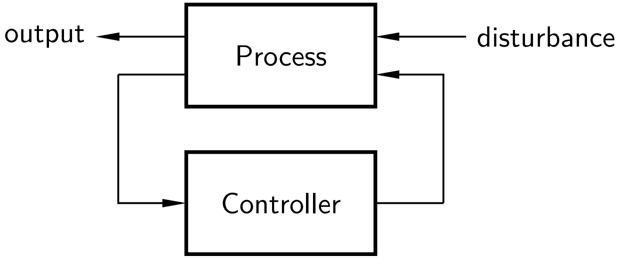
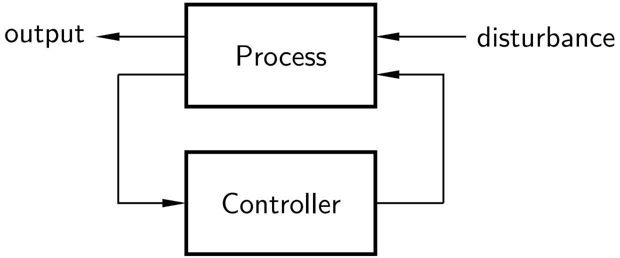
We need results on latency distributions

Outline

Controller design



Controller design



Controller objectives

- Stabilise the process
- Minimise the effect of the disturbance on the output

Worst-case control

H_∞ control: minimise the amplification of the worst-case disturbance

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- Theoretical worst-case noise amplification $= 1$

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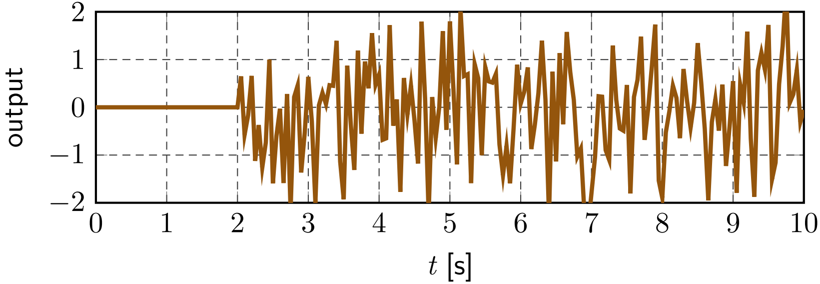
H_∞ control: minimise the amplification of the worst-case disturbance

- Theoretical worst-case noise amplification $= 1$
- Simulation with white noise disturbance applied from $t = 2$ s



- Empirical noise amplification $= 1$

Average-case control

H_2 control: minimise the amplification of a white noise disturbance

Average-case control

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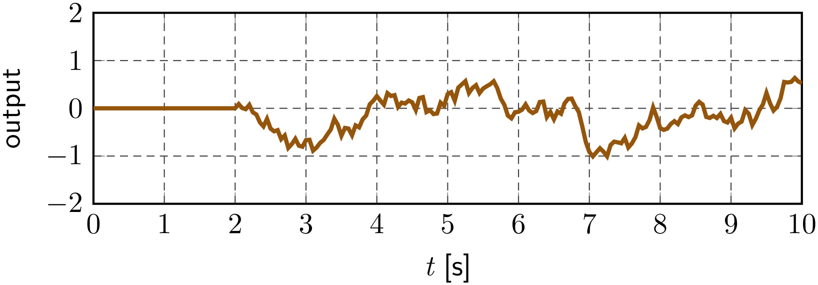
- Theoretical worst-case noise amplification $= 2$

Average-case control

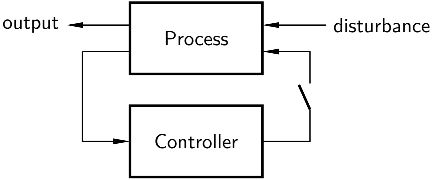
H_2 control: minimise the amplification of a white noise disturbance

- Theoretical worst-case noise amplification $= 2$
- Simulation with the same white noise disturbance applied from $t = 2$ s



- Empirical noise amplification $= 0.5$

Deadline miss handling[1]



[1] M. Seidel, M. Maggio, and F. Allgöwer. A controller synthesis framework for weakly-hard control systems. In *2026 IEEE 32nd Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 41–54. IEEE, May 2026. DOI: 10.1109/rtas68450.2026.00011.

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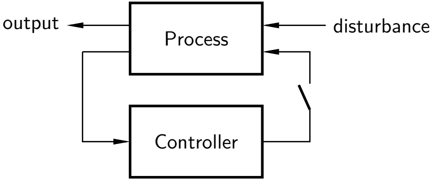

"Notably, the controllers perform better in extreme situations, which are closer to the worst case they are designed for."

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Outline

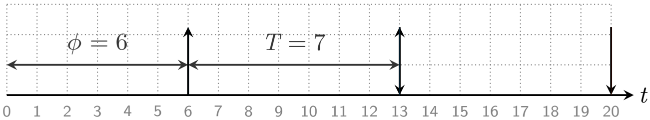
1 Worst-case versus average-case control

2 A brief review of end-to-end latency

3 Open problems

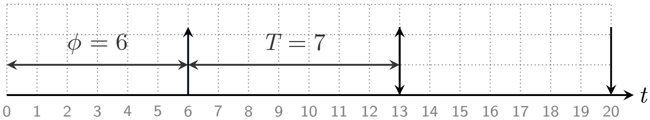
Tasks

Task τ with period T and phase ϕ



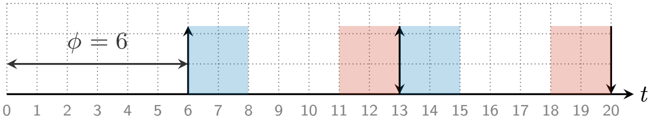
Tasks

Task τ with period T and phase ϕ

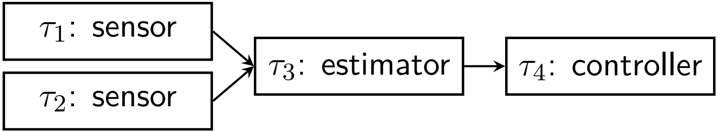


Read and write events in every period

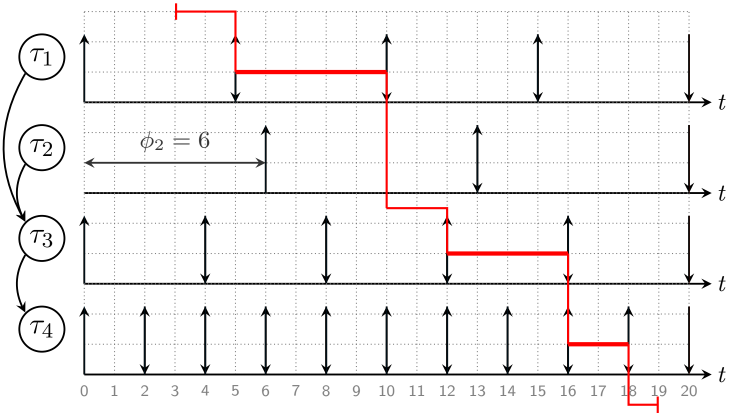
- Logical execution time (LET): at fixed points in time
- Implicit communication: within some intervals



Task chains and DAGs



Data paths


τ_1
τ_2
τ_3
τ_4
$\phi_2 = 6$
t
t
t
t
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Data age and reaction time

Latency properties of a data path

- Data age: age of input data, counted from actuation time
- Reaction time: time until output is generated, counted from arrival time

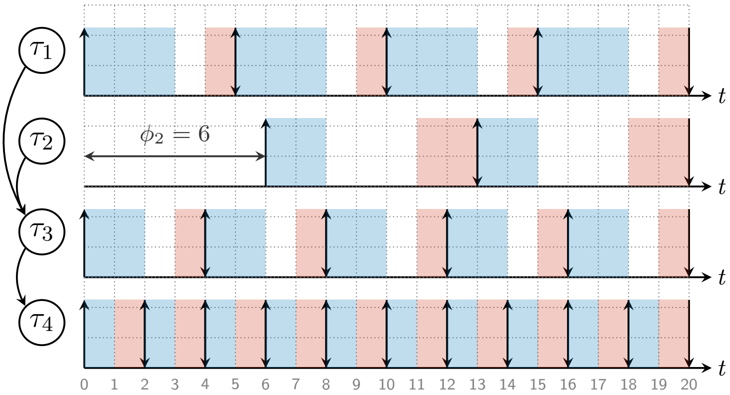
Control design: data age describes the data actually used by the controller

Probabilistic uncertainty in task chains

- Modelling randomness in task execution
- Aggregating complex patterns (e.g. schedules) using a probability distribution

Probabilistic uncertainty in task chains

- Jitter in read and write instants with probability distributions $f^{\mathsf{r}}, f^{\mathsf{w}}$



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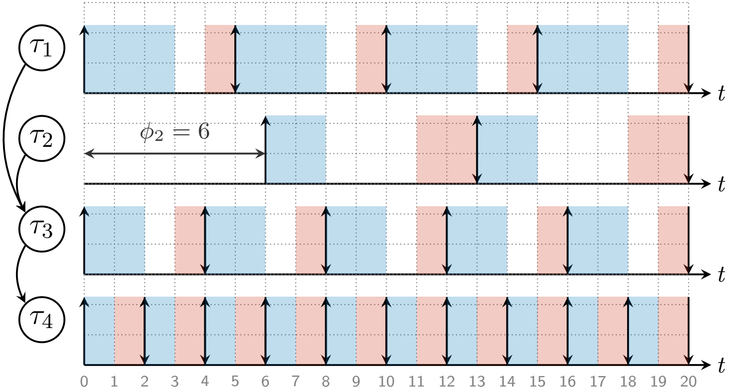

- Deadline misses or other losses with per-job failure probability

Worst-case end-to-end latency

The main focus of existing research[2]

- Maximum data age
- Maximum reaction time

[2] M. Günzel, H. Teper, G. v. d. Brüggen, and J.-J. Chen. End-to-end latency of cause-effect chains: a tutorial. *ACM Transactions on Embedded Computing Systems*, 24(1):1–18, Dec. 2024. ISSN: 1558-3465. DOI: 10.1145/3703630.

End-to-end latency distributions?

Probabilistic approaches focus on exceedance probabilities for worst-case metrics

[3] R. I. Davis and L. Cucu-Grosjean. A survey of probabilistic timing analysis techniques for real-time systems. *Leibniz Transactions on Embedded Systems (LITES)*, 6:03:1–03:60, 1, 2019. DOI: 10.4230/LITES-V006-I001-A003.

[4] M. Günzel, N. Ueter, K.-H. Chen, G. von der Brüggen, and J.-J. Chen. Probabilistic reaction time analysis. *ACM Transactions on Embedded Computing Systems*, 22(5s):1–22, Sept. 2023. ISSN: 1558-3465. DOI: 10.1145/3609390.

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Worst-case execution time[3]

- Randomness in hardware, software, or input data
- Overapproximation of the execution time distribution of tasks

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Maximum reaction time[4]

- Response time distributions or job failures
- Overapproximation of the reaction time distribution of task chains

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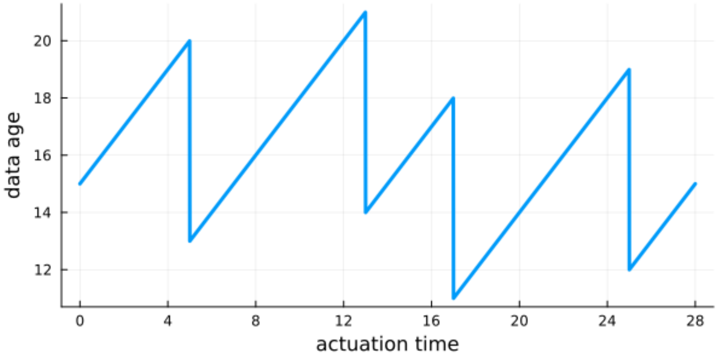
End-to-end latency distributions?

Even under LET (deterministic), latency varies over a hyperperiod[5]

Average data age from data age curve



[5] M. Günzel, M. Becker, and D. Casini. Shape-aware analysis of end-to-end latency under LET. In *2026 IEEE 32nd Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 82–95. IEEE, May 2026. DOI: 10.1109/rtas68450.2026.00014.

Outline

Open problem 1: Latency distributions under probabilistic uncertainty

Given a task chain specification, a communication semantic, and an uncertainty:

- read/write jitter
- job failure probabilities
- ...

Compute the probability distribution of the reaction time and data age of the task chain.

Open problem 1: Latency distributions under probabilistic uncertainty

- Equivalence between data age and reaction time distributions?[6]

[6] M. Günzel, H. Teper, K.-H. Chen, G. von der Brüggen, and J.-J. Chen. On the equivalence of maximum reaction time and maximum data age for cause-effect chains. en. In *35th Euromicro Conference on Real-Time Systems (ECRTS 2023)*. Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2023. DOI: 10.4230/LIPICS.ECRTS.2023.10.

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Open problem 1: Latency distributions under probabilistic uncertainty

- Equivalence between data age and reaction time distributions?[6]
- Aggregate metrics for DAGs
- Independence assumptions and scalability

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Open problem 2: Optimal control given a latency distribution

For a physical process controlled by a task chain, design a controller that

- achieves optimal performance given the data age distribution[7]
- has some worst-case guarantees

[7] J. Nilsson. *Real-Time Control Systems with Delays*. PhD thesis, Department of Automatic Control, Lund Institute of Technology (LTH), 1998.

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Codesign of controller and cause-effect chain

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